FACULTY OF ENGINEERING AND ARCHITECTURE

Acousto-electric Frequency Shifting and Filtering of Deep Neuronal Activity: A New Technique for Acousto-Electrophysiological Neuroimaging

Mehdi Soozande[1], Emmeric Tanghe[1], Thomas Tarnaud[1, 2]

[1] WAVES, Department of Information Technology (INTEC), Ghent University/IMEC, Tech Lane 126, 9052 Ghent, Belgium

[2] 4BRAIN, Department of Neurology, Ghent University Hospital, Corneel Heymanslaan 10, 9000 Ghent, Belgium

INTRODUCTION

Electrophysiological neuroimaging is critical for understanding brain function and diagnosing neurological disorders.

Challenge:
- EEG/MEG → high temporal resolution, poor spatial specificity
- fMRI → better spatial resolution, but slow and indirect

Goal: Non-invasive recording of deep brain activity with high spatial and temporal resolution

Solution – Acousto-electrophysiological Neuroimaging (AENI):
- Combines focused ultrasound (for deep, localized targeting) with electrophysiology (for direct neuronal signals)
- Ultrasound induces microscopic vibrations of neurons in the target region
- Vibrations cause frequency shifting of neural signals into sidebands around the ultrasound carrier
- Signals from target region → shifted and detectable
- Signals from non-target regions → remain unshifted, can be suppressed

Computational modelling:
- Validate the physical feasibility of ultrasound-induced frequency shifting.
- Optimize acoustic and electrophysiological parameters safely and efficiently.
- Predict signal characteristics and artifacts under controlled conditions.

Impact:
- Enables selective extraction of deep neuronal activity
- Enhances spatial resolution while maintaining millisecond temporal resolution
- Potential applications in neuroscience research and clinical diagnostics

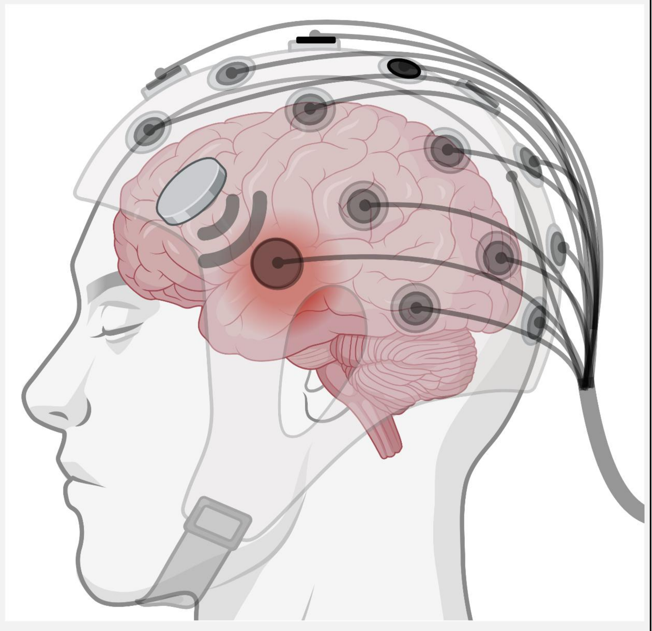


Figure 1: AENI: integration of focused ultrasound with electrophysiological recording (Created by Biorender)

METHODS

Generating Acousto-Electric LFP Signals

Neuron Model:
- Implemented a simple ball-and-stick neuron in NetPyNE
- Stimulated electrically via somatic current injection
- Electrode Placement: Virtual LFP electrode positioned 50 μm from the middle of the axon (ref. electrode: infinity)

Ultrasound Modelling:
- Planar ultrasound wave applied as a homogeneous vibration of the neuron relative to the electrode
- Displacement amplitude determined by applied ultrasound pressure
- Vibration frequency matched to the ultrasound carrier frequency

Signal Generation: vibration of neuron changes electrode-neuron distance, producing acousto-electric frequency shifting of recorded LFP signals

Figure 2: LFP recording of a single neuron (Created by ChatGPT)

Decoding Targeted Neural Activity

Bandpass filter
- IIR 20th-order Butterworth filter
- Center frequency: ultrasound frequency (0.5 MHz, 1 MHz)
- Bandwidth: 30 kHz

Lowpass filter
- IIR Butterworth filter
- Passband: 1 kHz
- Stopband: 2 kHz
- Stopband attenuation: 60 dB

Demodulation
- Frequency: ultrasound central frequency

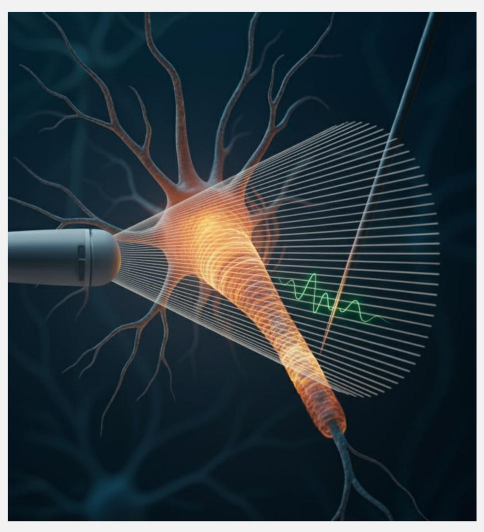
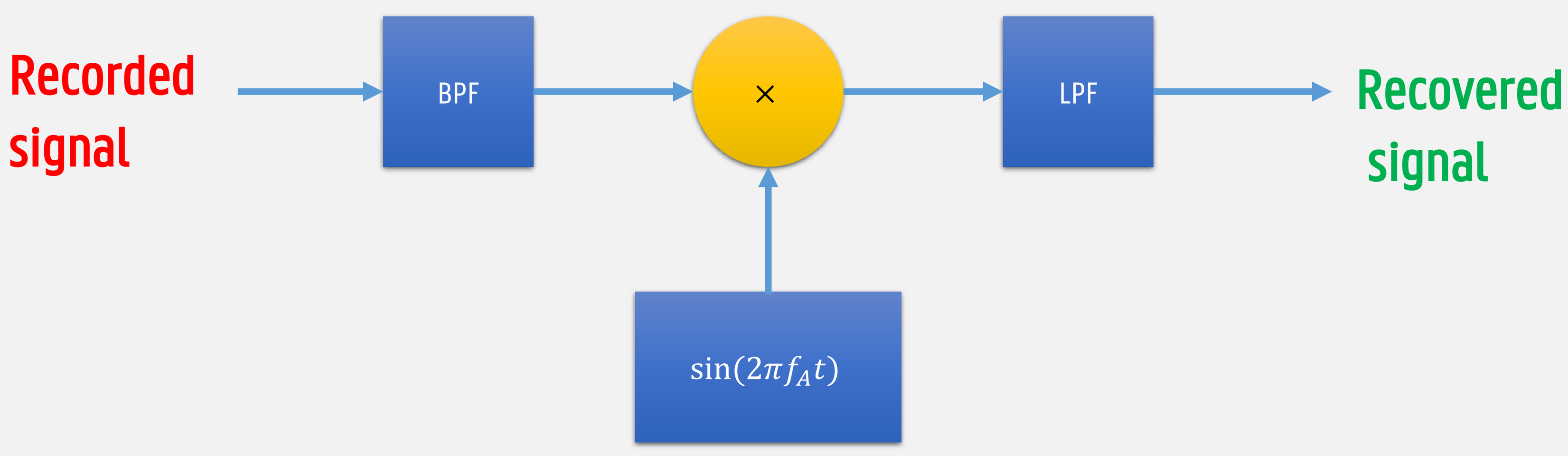
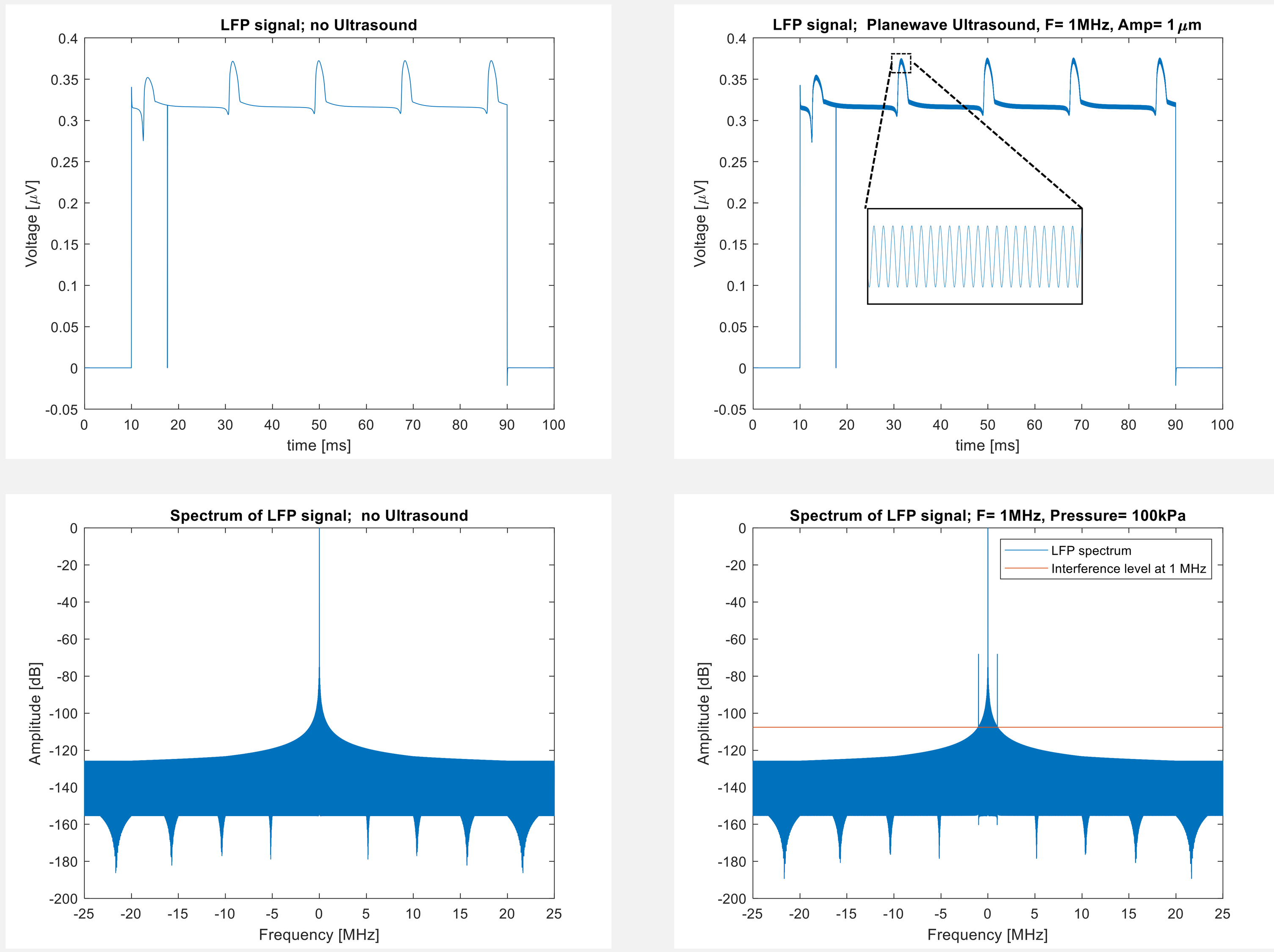


Figure 3: ultrasound-induced neuron vibration and LFP recording (Created by ChatGPT)

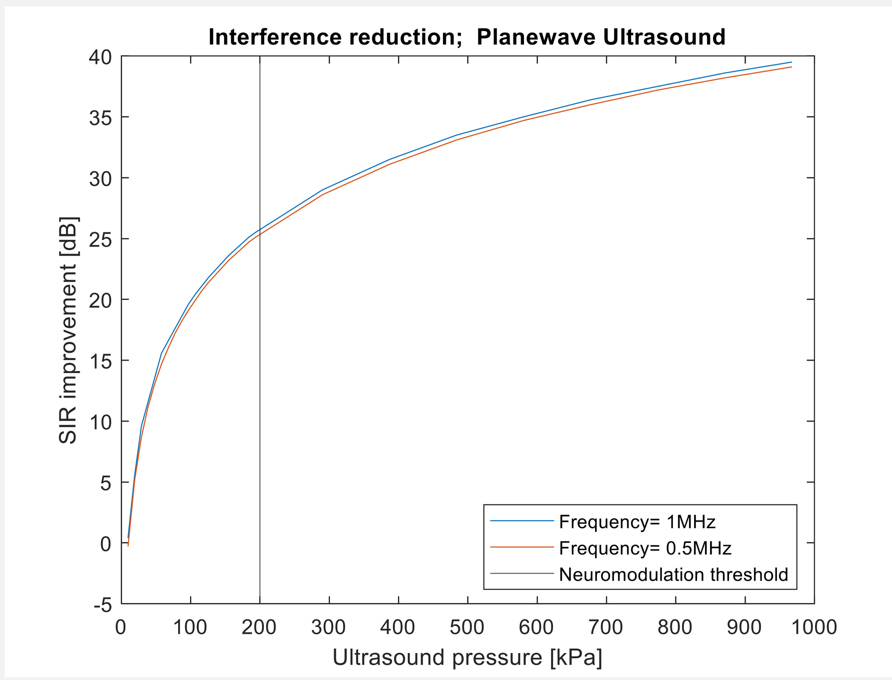


RESULTS

LFP signals and spectrums:



Signal to interference ratio (SIR): $$\frac{\textit{Spectrum amplitude of LFP at ultrasound center frequency}}{\textit{Interference level at ultrasound center frequency}}$$



- **Lower ultrasound frequency ➔ Higher displacement for a given pressure**
- **Higher displacement ➔ higher SIR**
- **Lower ultrasound frequency ➔ higher interference**

Ultrasound frequency optimization for highest SIR

CONCLUSIONS

- AENI leverages ultrasound-induced frequency shifting for spatially selective neural recording.
- Frequency-domain decoding isolates activity from targeted regions while suppressing interference.
- NetPyNE simulations show up to 25 dB SIR improvement at subthreshold ultrasound pressures.

FUTURE WORKS

- More realistic simulations: morphologically realistic cells, realistic pressure field distributions
- optimization of protocols and electrodes/transducers to maximize SNR and SIR
- In vivo and in vitro experimental validation

Contact
mehdi.soozande@ugent.be

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